

Solar Neutrinos - The Dawning of a ν Era

- Solar neutrinos

 - Sudbury Neutrino Observatory (SNO)

- Terrestrial reactor antineutrinos

 - Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND)

- The ν era

 - new questions and precision measurements



CENPA

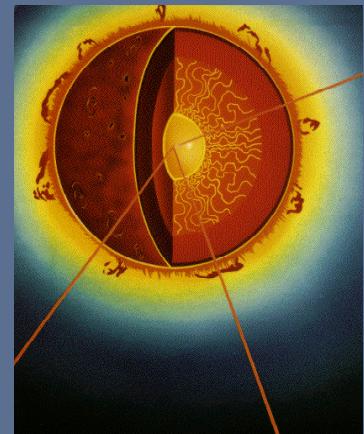
Center for Experimental Nuclear Physics and Astrophysics
University of Washington

J. F. Wilkerson

February 15, 2004

AAAS Matter at Minute Dimensions

The Sun's source of energy



1854 von Helmholtz postulates gravitational energy

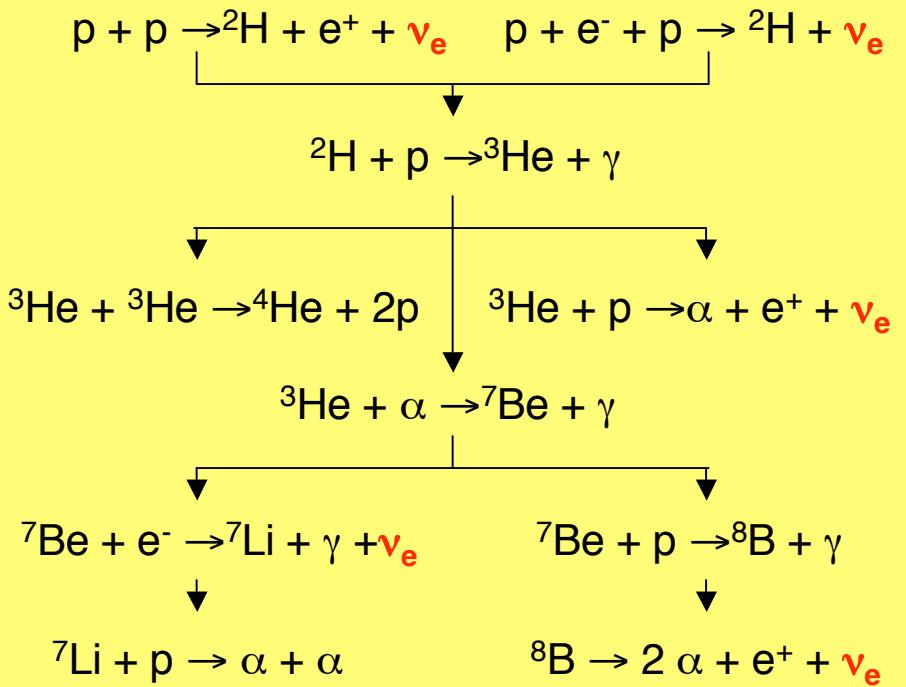
1920's Eddington proposes p + p fusion

"We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place."

1938 Bethe & Critchfield



SSM Energy Generation

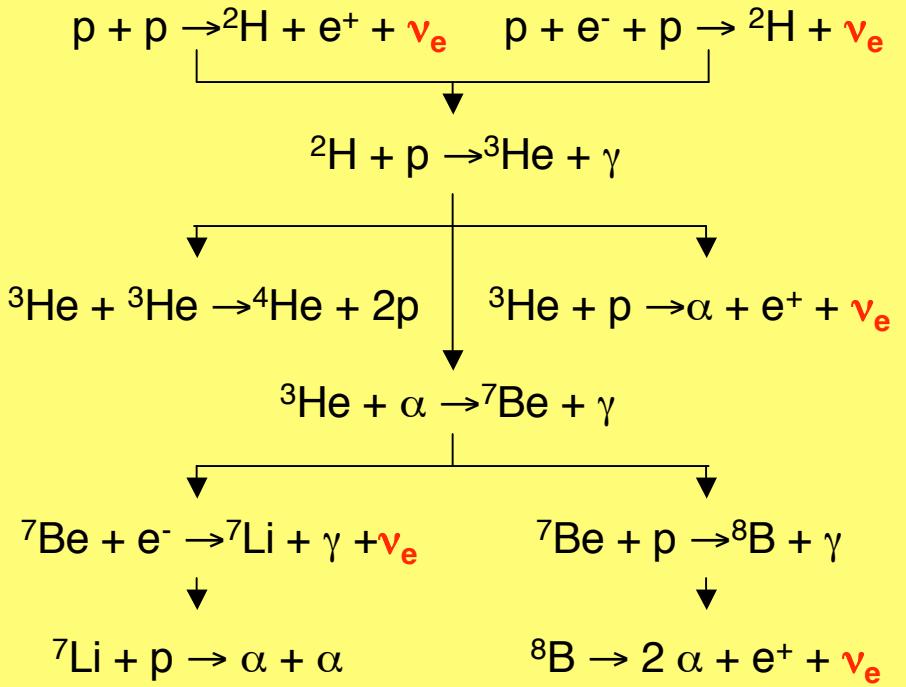


Using solar νs' to probe the Sun

1946 Pontecorvo, 1949 Alvarez



SSM Energy Generation



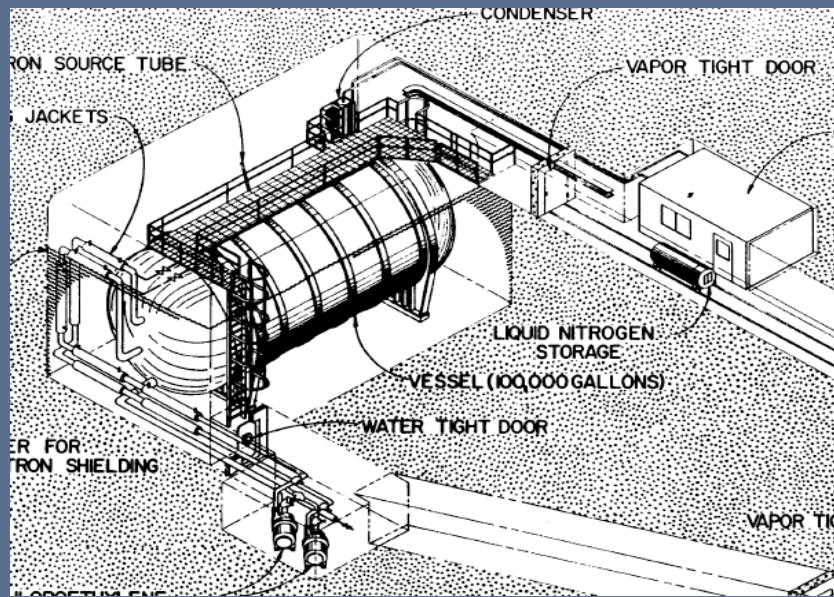
Using solar ν s' to probe the Sun

1946 Pontecorvo, 1949 Alvarez



1960's

Ray Davis, builds
Chlorine detector



Neutrino Energy (MeV)

Using solar ν s' to probe the Sun

1946 Pontecorvo, 1949 Alvarez

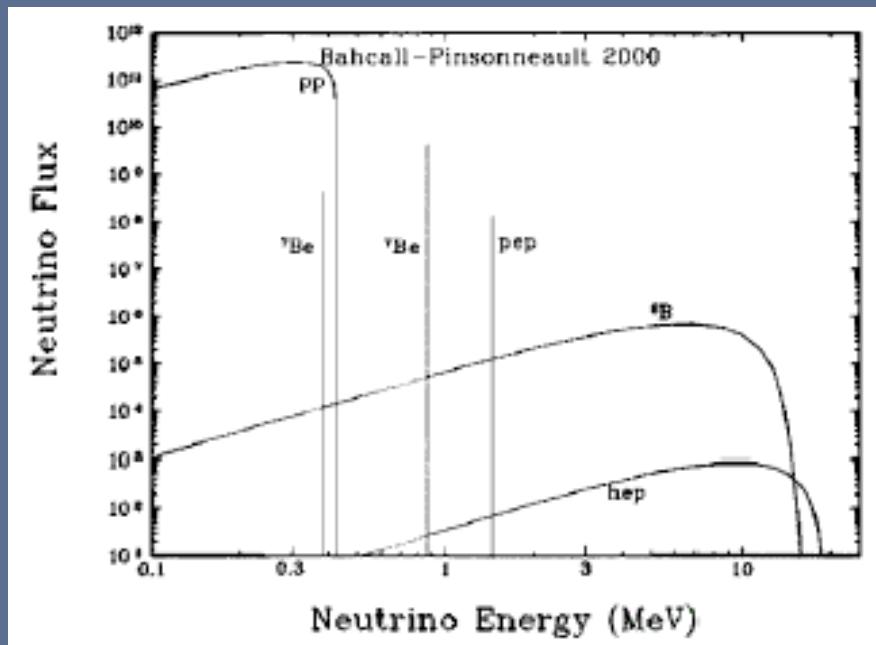


1960's

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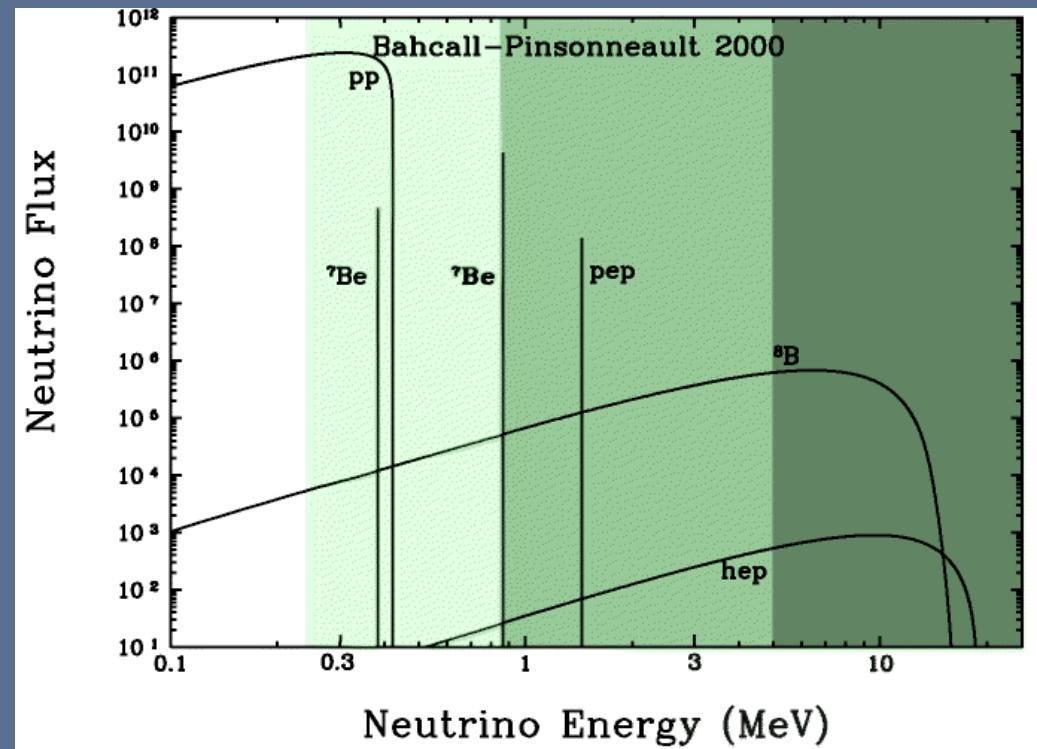
John Bahcall, generates
SSM & ν flux predictions

“...to see into the interior of a star
and thus verify directly the
hypothesis of nuclear energy
generation in stars...”



Solar ν Flux Measurement Results

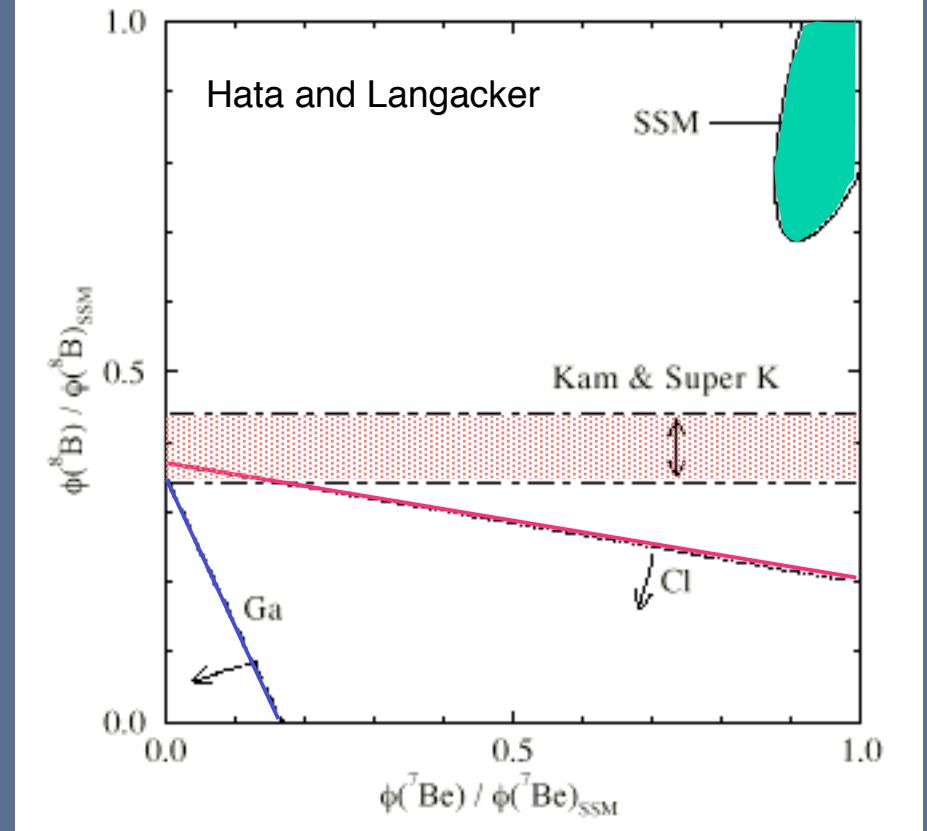
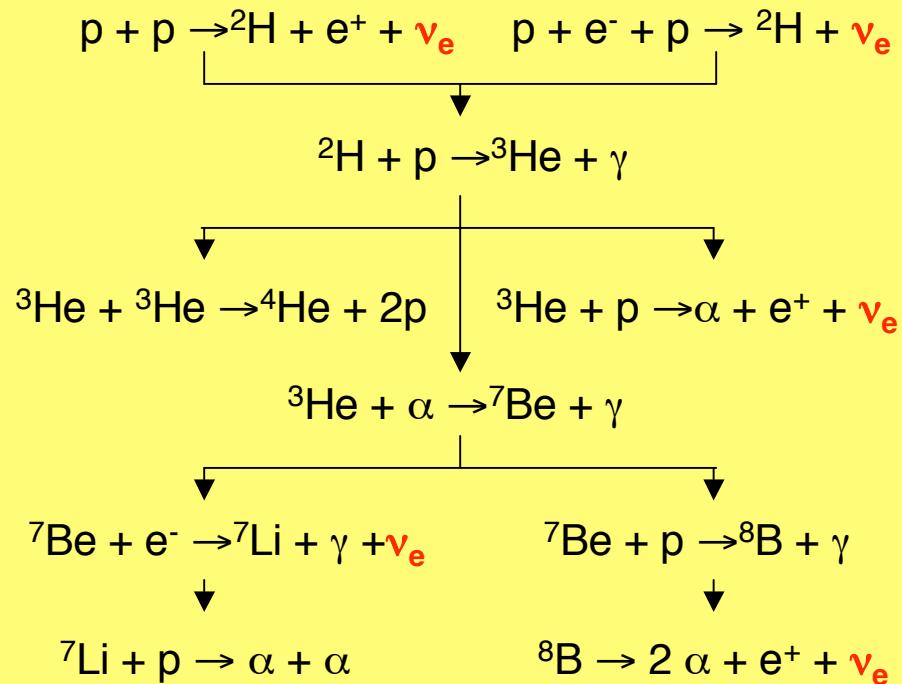
$\int \text{solar } \nu \text{ flux}$
 $\sim 6.5 \cdot 10^{10} / \text{cm}^2/\text{s}$



Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$

Astrophysical Solutions?

SSM Energy Generation



The data are incompatible with standard and non-standard solar models

(For a model independent analysis see Heeger and Robertson, PRL 77 (1996) 3720)

Super-Kamiokande

PRL 86 5651 (2001)

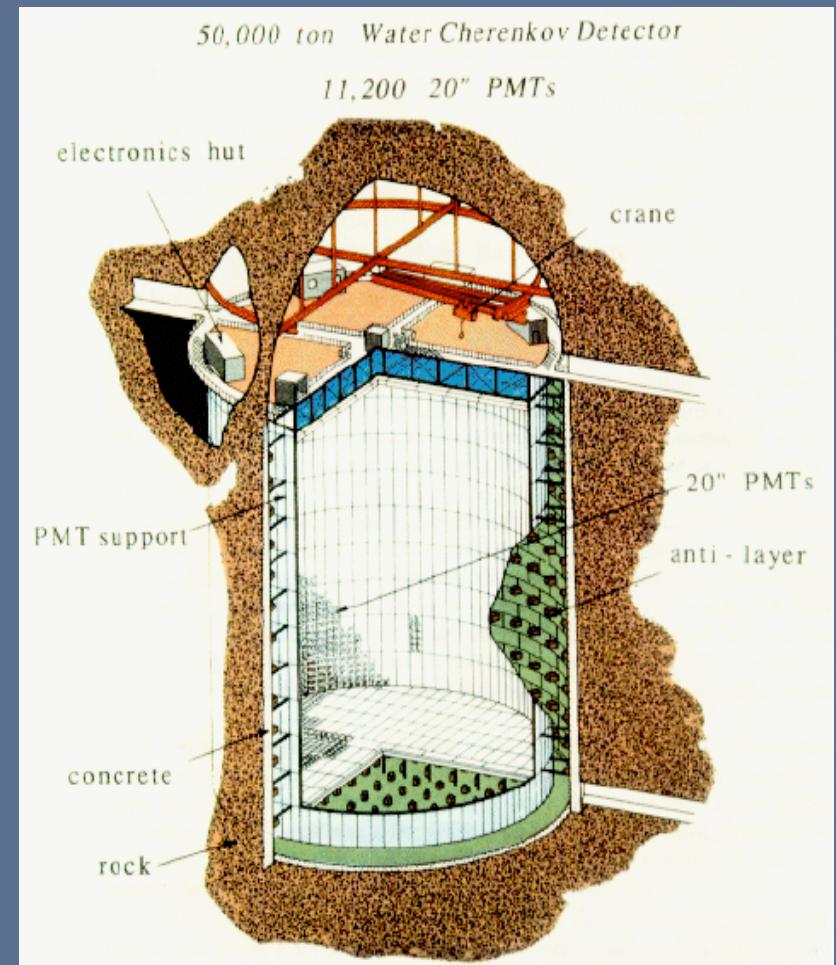
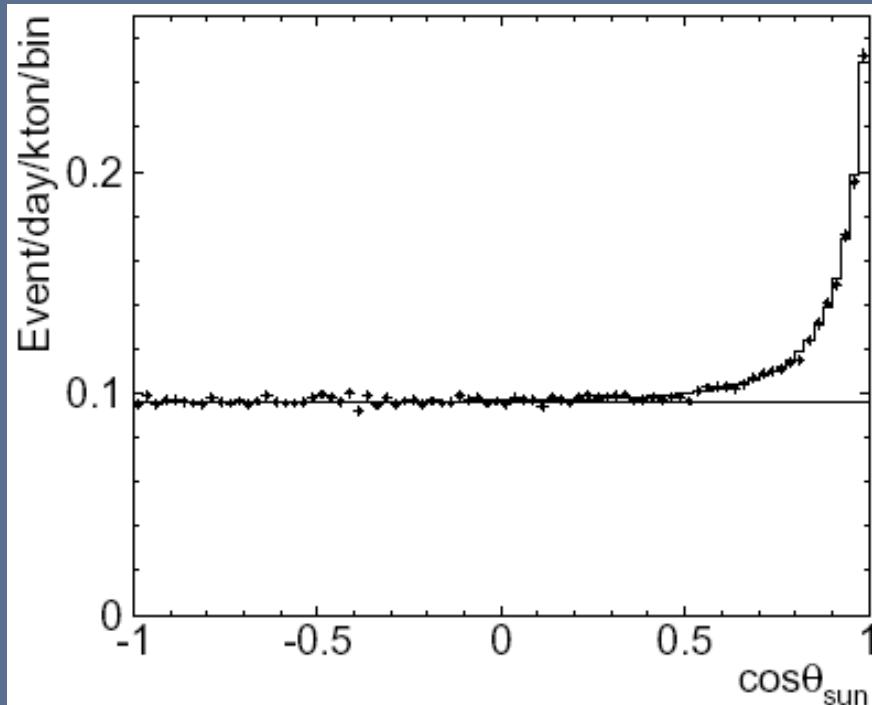


$$\Phi^{\text{ES}} = 2.32 \pm 0.03 \begin{array}{l} +0.08 \\ -0.07 \end{array} \quad (10^6 \text{ cm}^{-2} \text{ s}^{-1})$$

(stat) (sys.)

$$\text{Data/SSM} = 0.451 \pm 0.005 \begin{array}{l} +0.016 \\ -0.014 \end{array}$$

(stat) (sys.)



Gallium Measurements

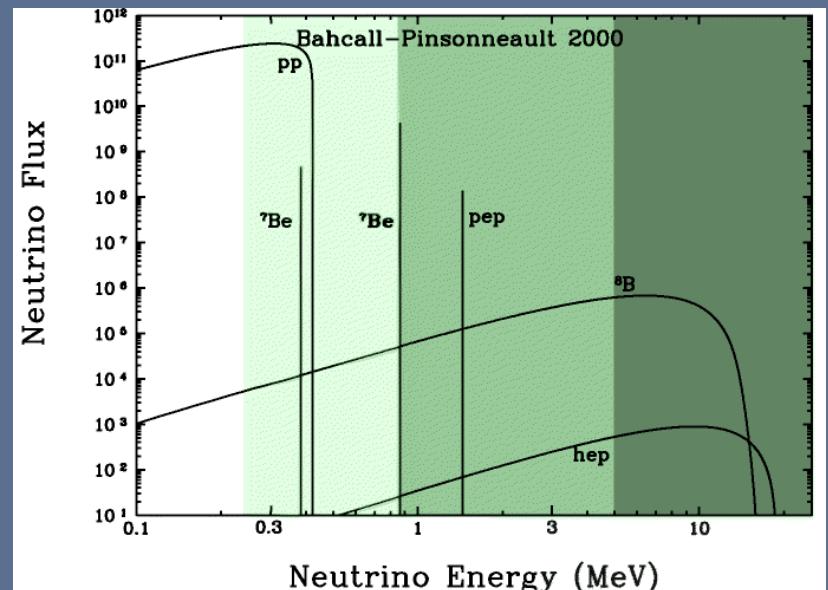
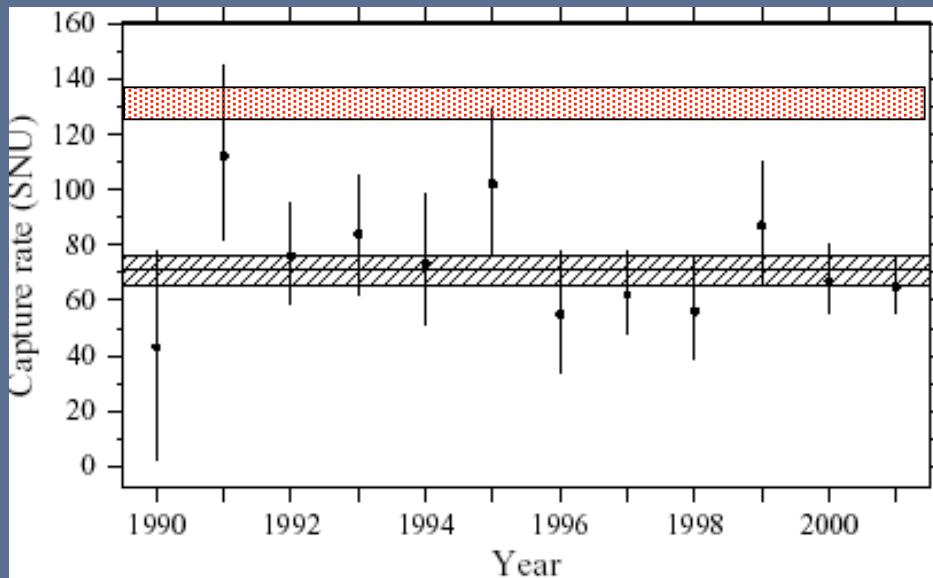


Two independent experiments

SAGE Data/SSM = 0.55 ± 0.05

GALLEX Data/SSM = 0.57 ± 0.05

Latest SAGE results (astro-ph/0204245)



Gallium Measurements

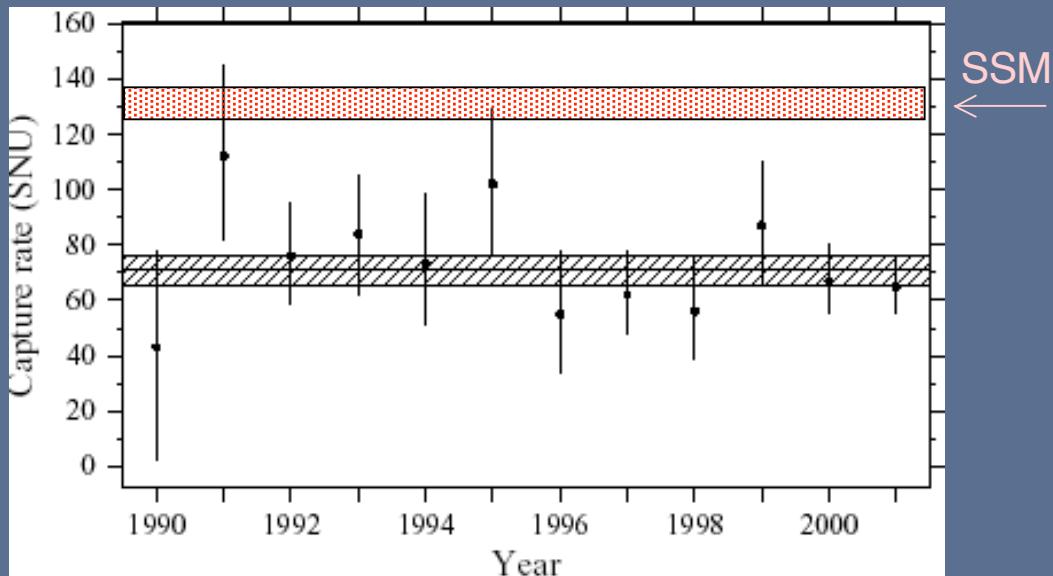


Two independent experiments

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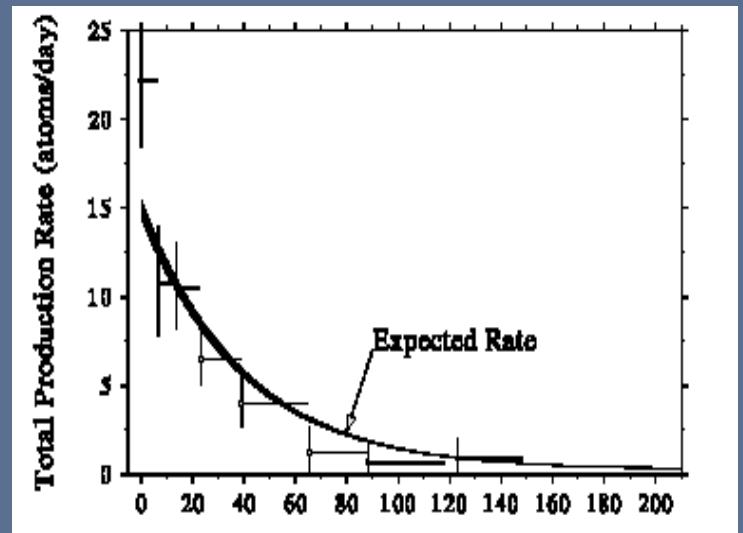
Latest SAGE results (astro-ph/0204245)



Both Expts Performed
ν source tests



SAGE Source Test
 $R(\sigma_{\text{mea}}/\sigma_{\text{th}}) = 0.95 \pm .12 \pm .03$

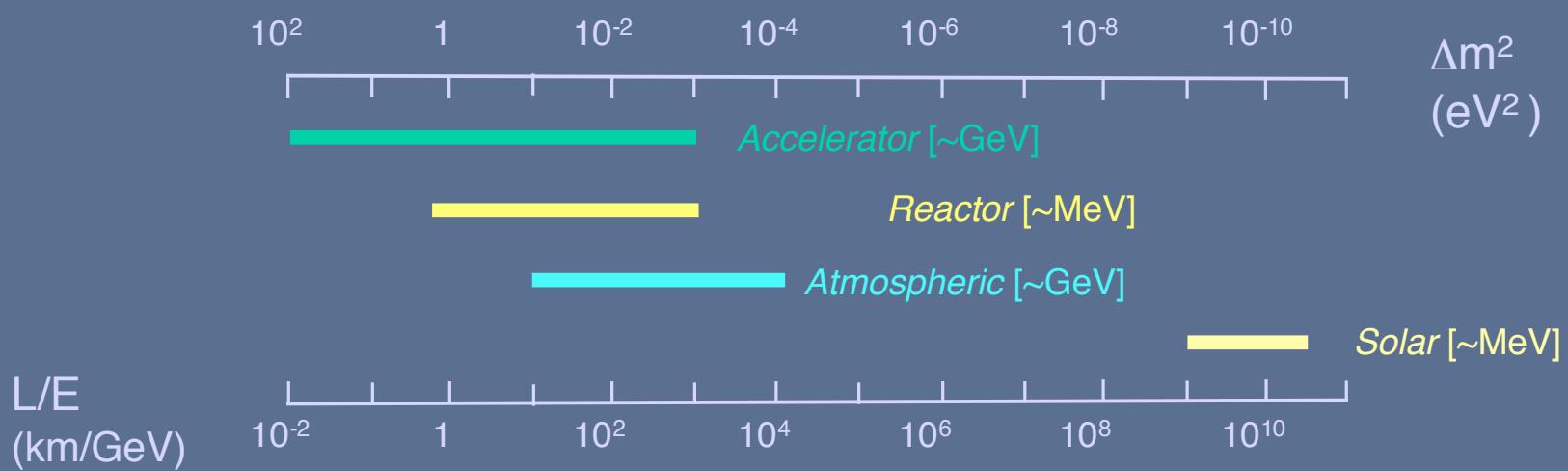


Sensitivity of experiments to ν oscillations

For simple case of mixing between
two ν mass eigenstates

$$P_{\nu_i \rightarrow \nu_j} = 4|U_{i2}|^2|U_{j2}|^2 \sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E_\nu}\right)$$

$$P_{\nu_i \rightarrow \nu_j} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2_{(\text{eV})} L_{(\text{km})}}{E_\nu (\text{GeV})}\right)$$



Sensitivity of experiments to ν oscillations

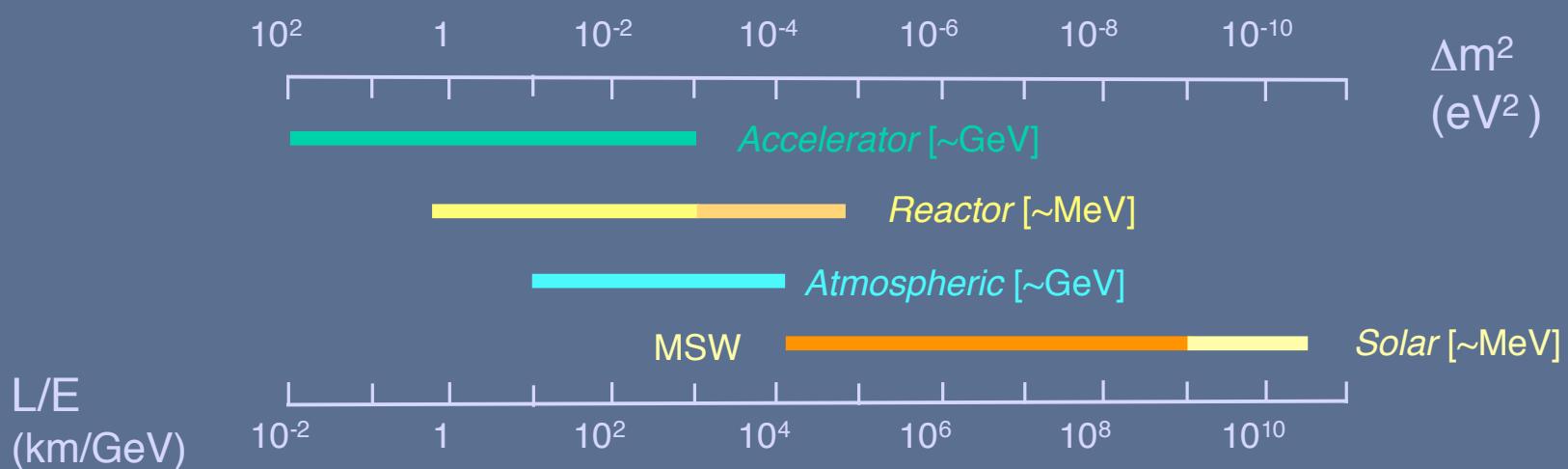
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$$P_{\nu_i \rightarrow \nu_j} = 4|U_{i2}|^2|U_{j2}|^2 \sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E_\nu}\right)$$

$$P_{\nu_i \rightarrow \nu_j} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2_{(\text{eV})} L_{(\text{km})}}{E_\nu (\text{GeV})}\right)$$

Matter Enhanced Oscillations (MSW)

ν s in matter can acquire an effective mass through scattering (analogous to index of refraction for light in transparent media)



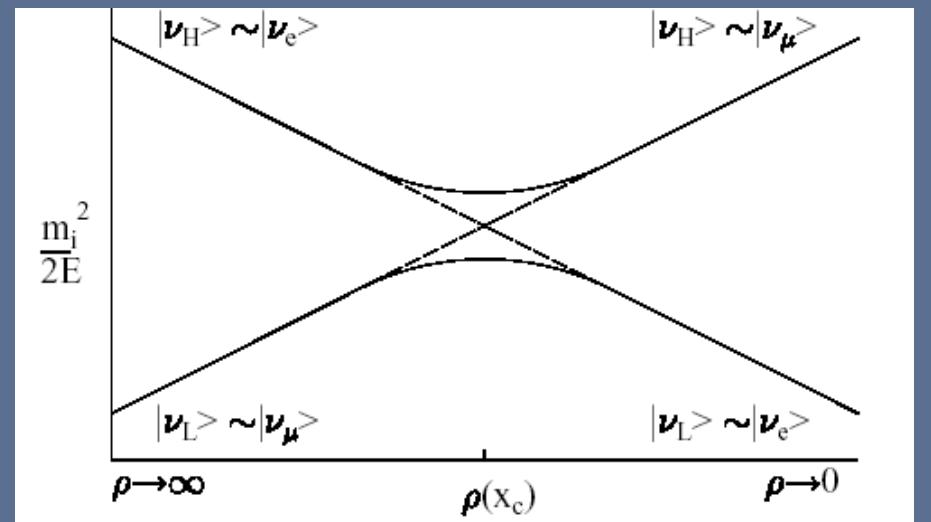
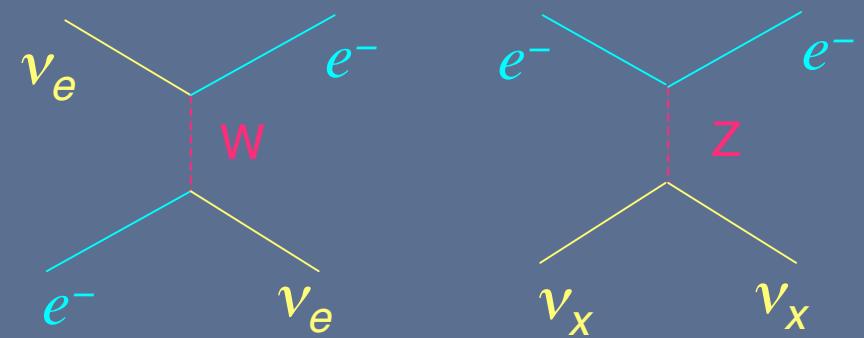
Mikheev, Smirnov, Wolfenstein Effect

Matter Enhanced Oscillations

ν s in matter can acquire an effective mass through scattering (analogous to index of refraction for light in transparent media)

Normal Matter contains many electrons, but no muons or taus, so ν_e can undergo both CC and NC scattering. Have QM two-state level crossing and flavor change.

MSW Oscillations are dependent on the ν energy and the density of the material, hence one can observe spectral energy distortions.



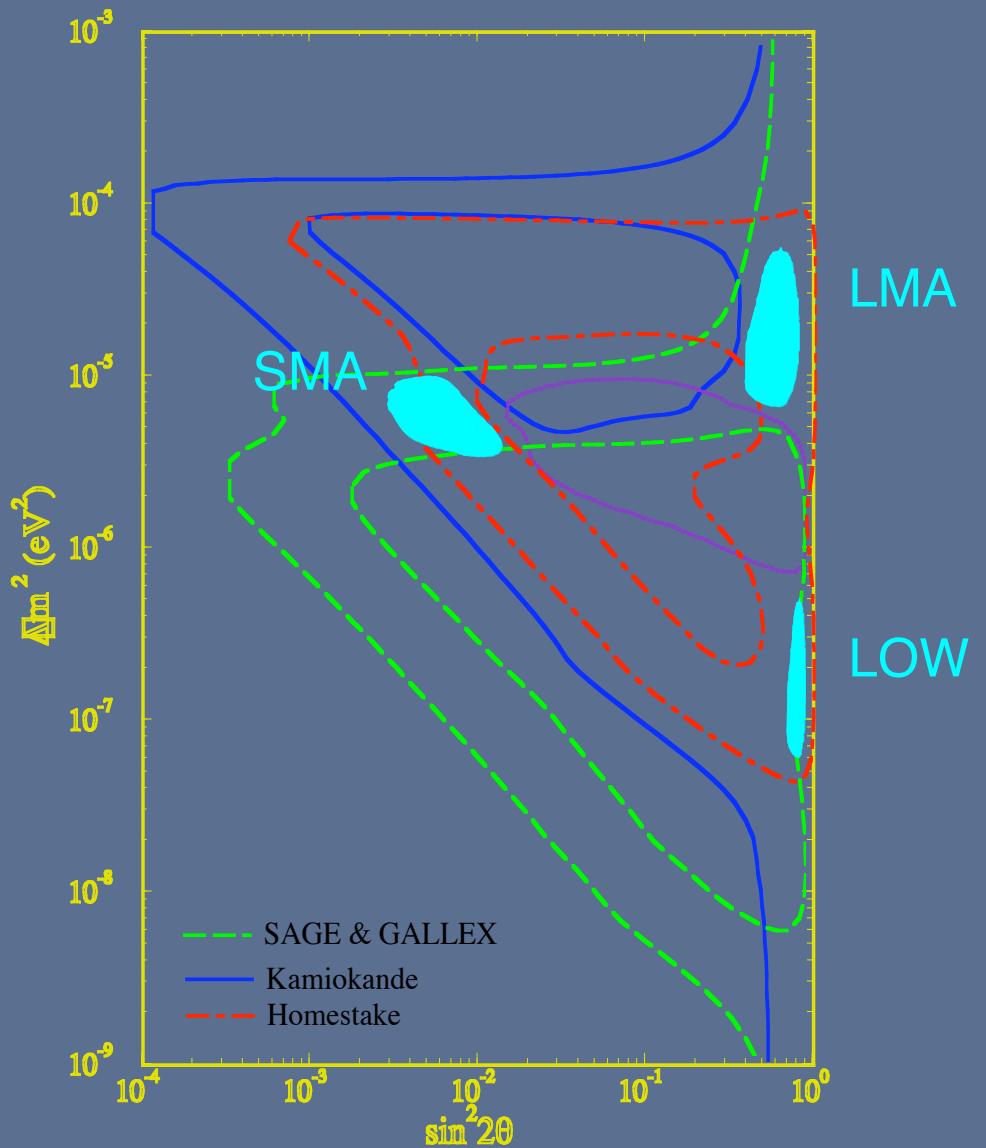
Matter Enhanced ν Oscillations

MSW gives a dramatic extension of oscillation sensitivity to potential regions in Δm^2

Solar ν data are consistent with the MSW hypothesis.

But circumstantial evidence

- Need definitive proof
- Appearance measurement
- Independent of SSM





The SNO Collaboration



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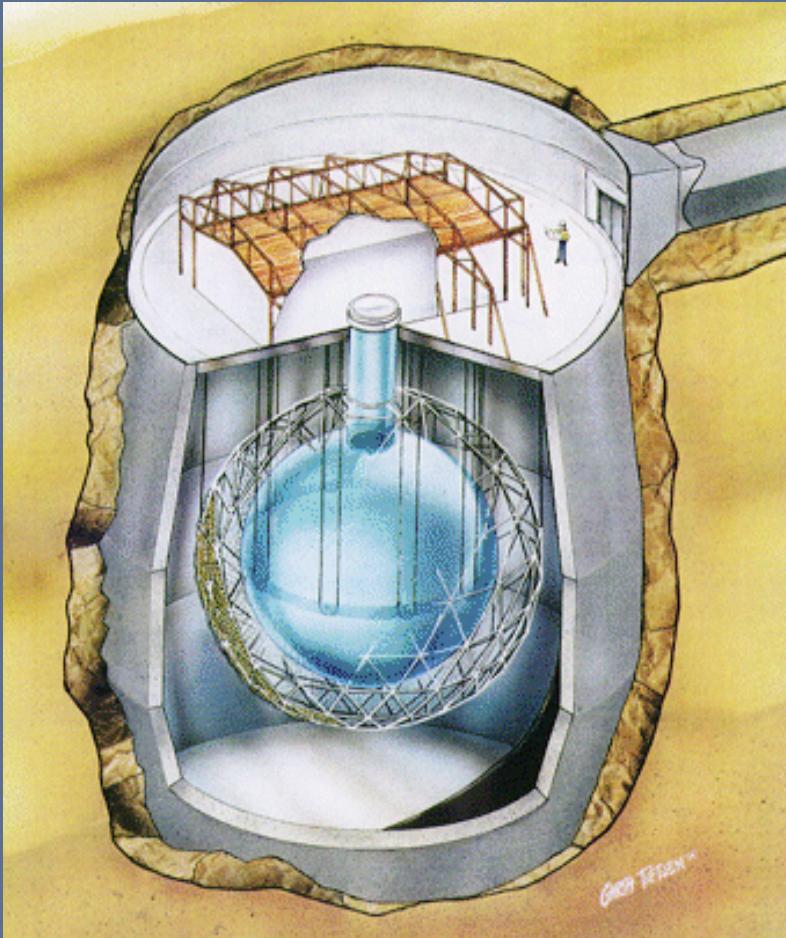
E. Bonvin, M. Chen, E.T.H. Clifford, F.A. Duncan, E.D. Earle,
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The Sudbury Neutrino Observatory



cc

$$\nu_e + d \Rightarrow p + p + e^-$$

- Good sensitivity to ν_e energy spectrum
- Weak directional sensitivity $\propto 1 - 1/3\cos(\theta)$
- ν_e only.

NC

$$\nu_x + d \Rightarrow p + n + \nu_x$$

- Measure total 8B ν flux from the sun.
- Equal cross section for all ν types
- 2.2 MeV Threshold, Integrated $E > E_{th}$

ES

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

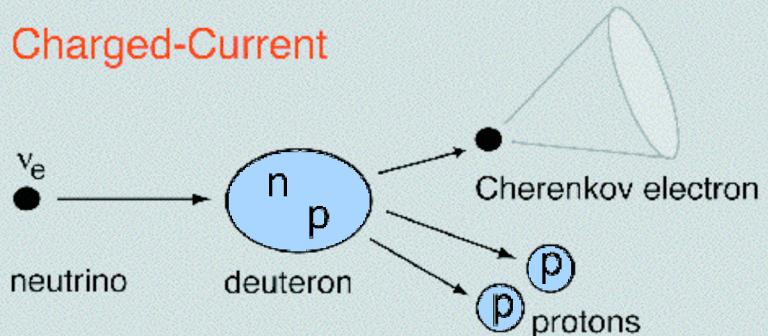
- Low Statistics
- Dominant contribution (5/6) from ν_e , smaller contributions from ν_μ & ν_τ
- Strong directional sensitivity



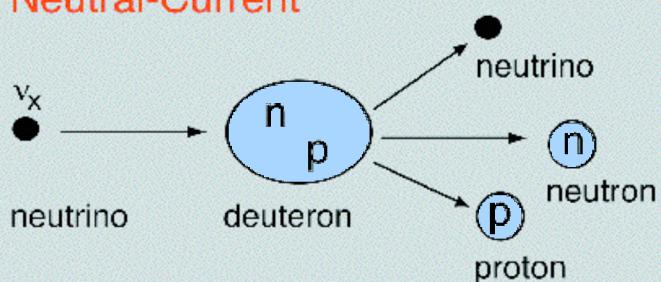
The Sudbury Neutrino Observatory

Neutrino Reactions on Deuterium

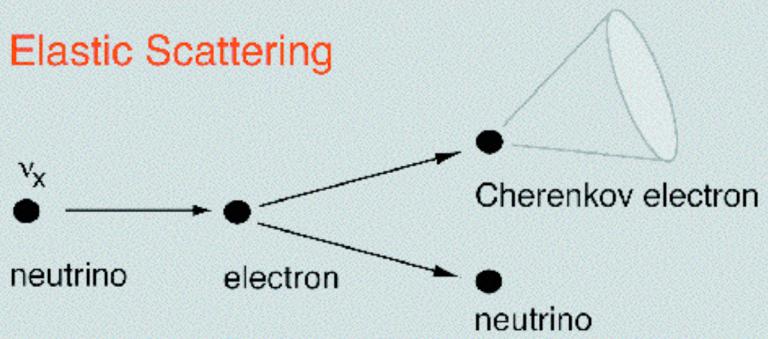
Charged-Current



Neutral-Current



Elastic Scattering



cc

$$\nu_e + d \Rightarrow p + p + e^-$$

- Good sensitivity to ν_e energy spectrum
- Weak directional sensitivity $\propto 1 - 1/3\cos(\theta)$
- ν_e only.

NC

$$\nu_x + d \Rightarrow p + n + \nu_x$$

- Measure total ^{8}B ν flux from the sun.
- Equal cross section for all ν types
- 2.2 MeV Threshold, Integrated $E > E_{th}$

ES

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

- Low Statistics
- Dominant contribution (5/6) from ν_e , smaller contributions from ν_μ & ν_τ
- Strong directional sensitivity

Key signatures for unexpected ν Flavors

Measure total flux of solar neutrinos vs. the pure ν_e flux

Direct Evidence for ν flavor change

$$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$

Potential signal
For ν oscillations

$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

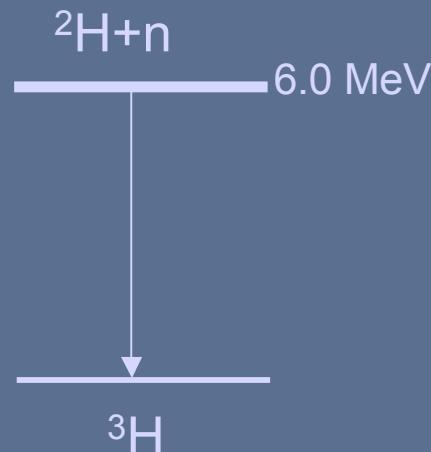
$$\Phi_{\text{day}} \quad \text{vs} \quad \Phi_{\text{night}}$$

SNO - three different NC detection methods

Phase I (D_2O)

Nov. 99 - May 01

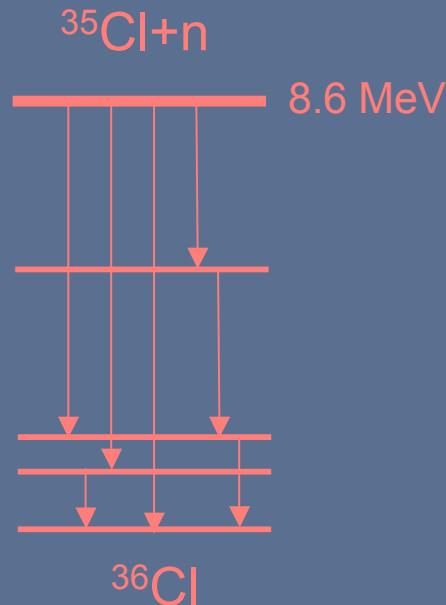
n captures on
 $^2H(n, \gamma)^3H$
 $\sigma = 0.0005 \text{ b}$
Observe 6.25 MeV γ
PMT array readout
Strong CC-NC Corr.



Phase II ("salt")

July 01 - Sep. 03

2 t NaCl. n captures on
 $^{35}Cl(n, \gamma)^{36}Cl$
 $\sigma = 44 \text{ b}$
Observe 8.6 MeV γ 's
PMT array readout
Strong CC-NC Corr.



Phase III (NCD)

Spring 04 - 2006

40 proportional counters
 $^3He(n, p)^3H$
 $\sigma = 5330 \text{ b}$
Observe p and 3H
Proportional counters
 ~ 0 CC-NC Corr.



SNO - three different NC detection methods

Phase I (D_2O)

Nov. 99 - May 01

n captures on
 $^2H(n, \gamma)^3H$
 $\sigma = 0.0005 \text{ b}$
Observe 6.25 MeV γ
PMT array readout
Strong CC-NC Corr.

- 306.4 live days
- 2928 events
- $T_e > 5 \text{ MeV}$
- $R < 550 \text{ cm}$
- T_e constrained
- use radial disc.

PRL 87, 071301, 2001

PRL 89, 011301, 2002

PRL 89, 011302, 2002

Phase II (“salt”)

July 01 - Sep. 03

2 t NaCl. n captures on
 $^{35}Cl(n, \gamma)^{36}Cl$
 $\sigma = 44 \text{ b}$
Observe 8.6 MeV γ 's
PMT array readout
Strong CC-NC Corr.

- 254.2 live days (July 01-Oct 02)
- 3055 events
- $T_e > 5.5 \text{ MeV}$
- $R < 550 \text{ cm}$
- T_e unconstrained
- use isotropy

nucl-ex/0309004

Phase III (NCD)

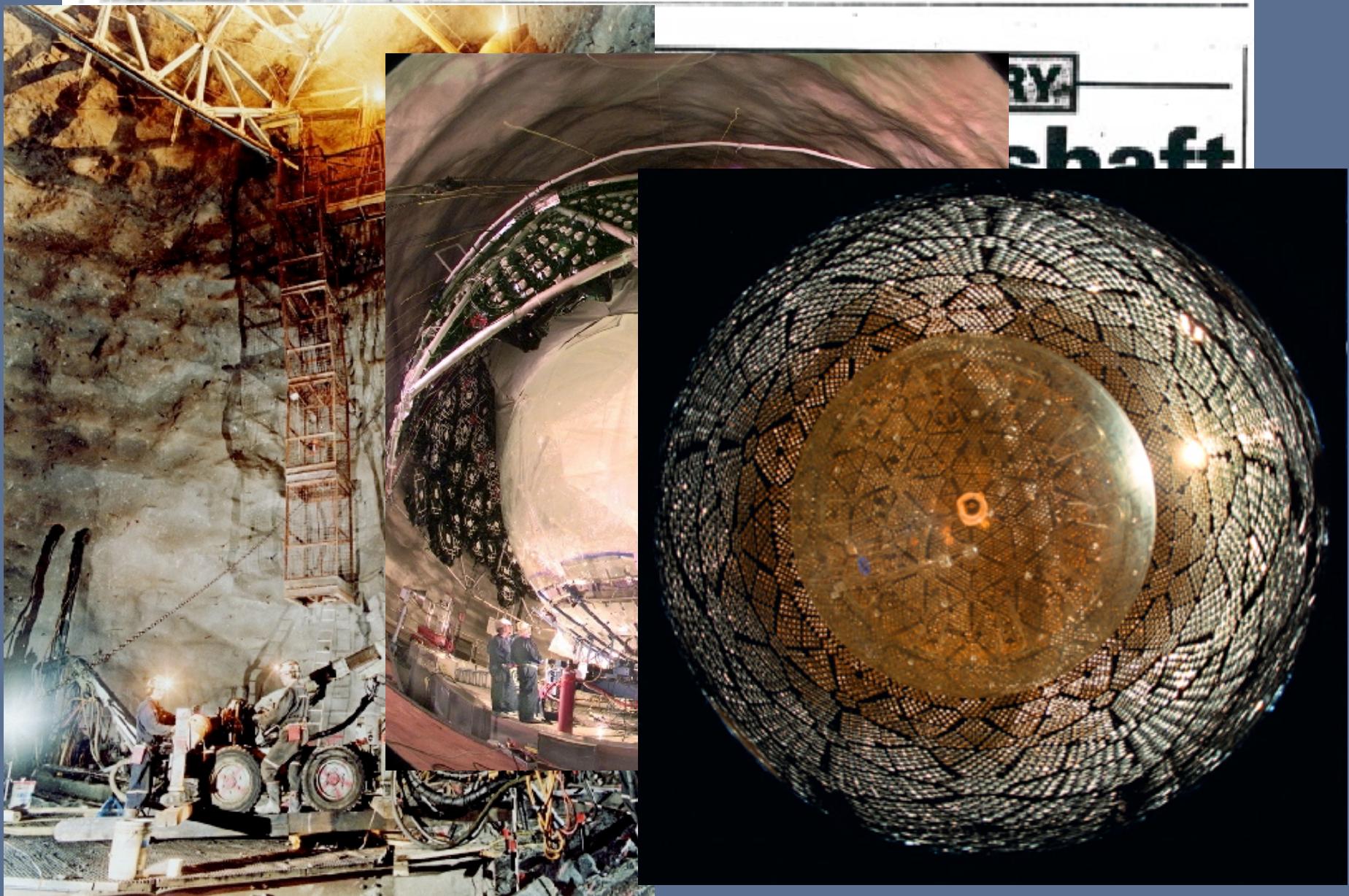
Spring 04 - 2006

40 proportional counters
 $^3He(n, p)^3H$
 $\sigma = 5330 \text{ b}$
Observe p and 3H
Proportional counters
~0 CC-NC Corr.

- Deployment complete
- Commissioning underway
- Expect smaller NC systematic uncertainties

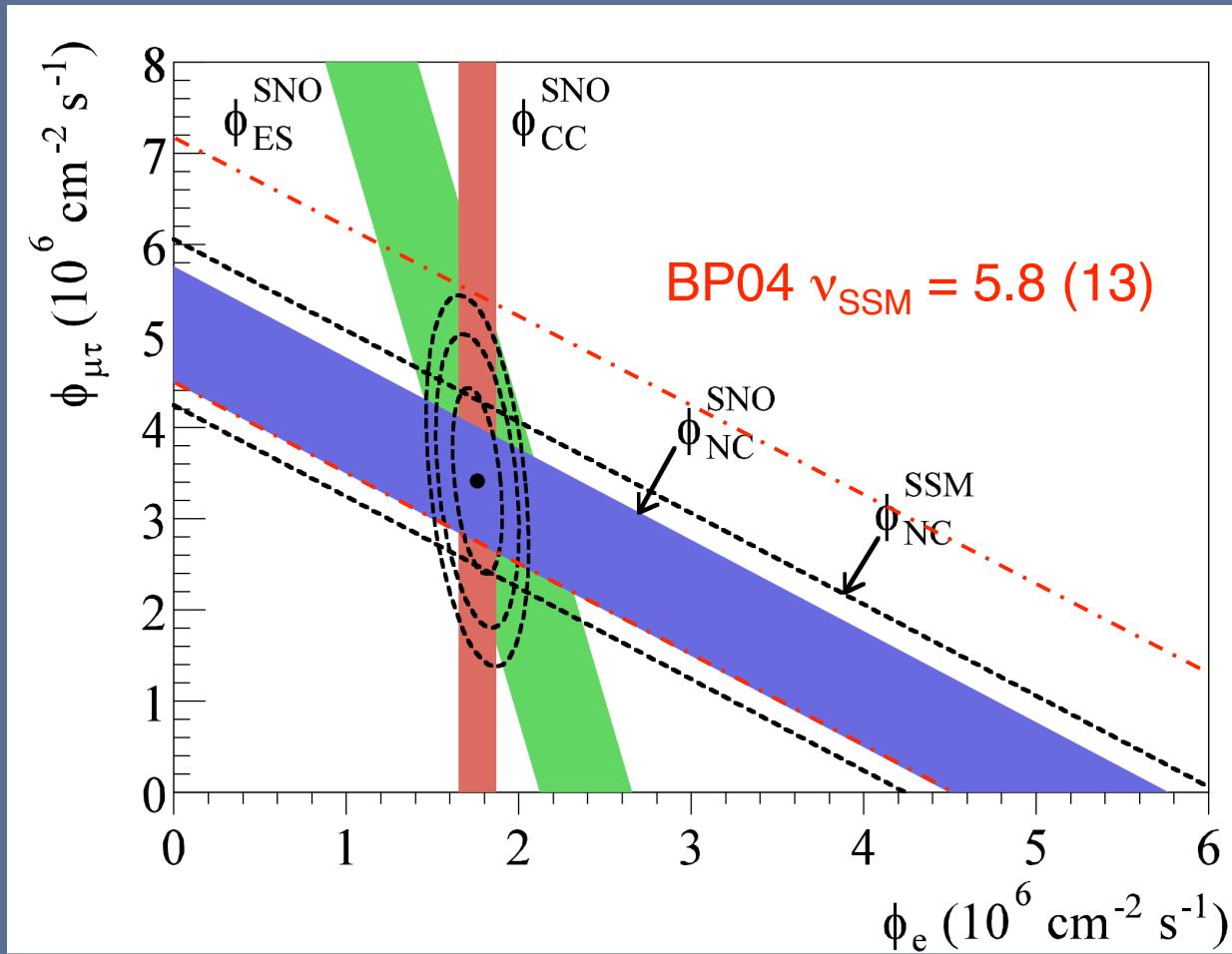


The SNO Detector during Construction



SNO Phase I (D_2O) Results

$\sim 2/3$ of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$



Fluxes ($10^6 \text{ cm}^{-2} \text{ s}^{-1}$)	
ν_e :	1.76(11)
$\nu_{\mu\tau}$:	3.41(66)
ν_{total} :	5.09(64)
ν_{SSM} :	5.05

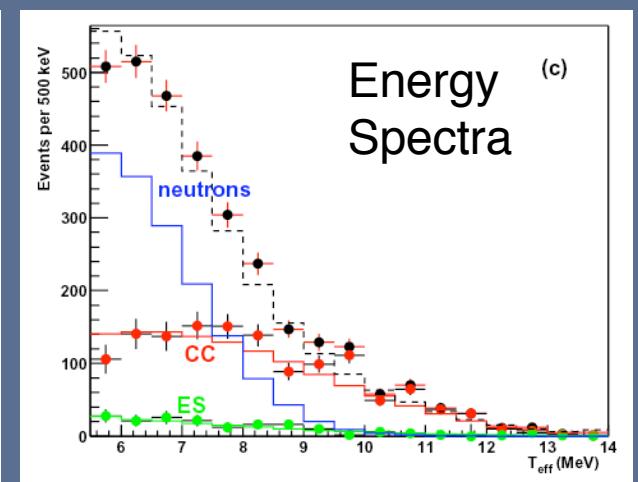
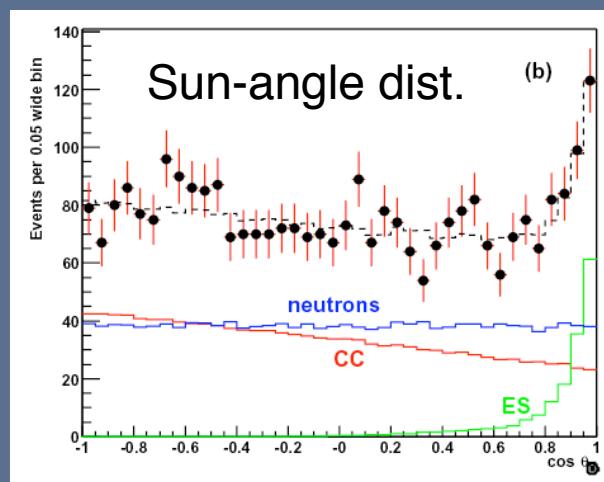
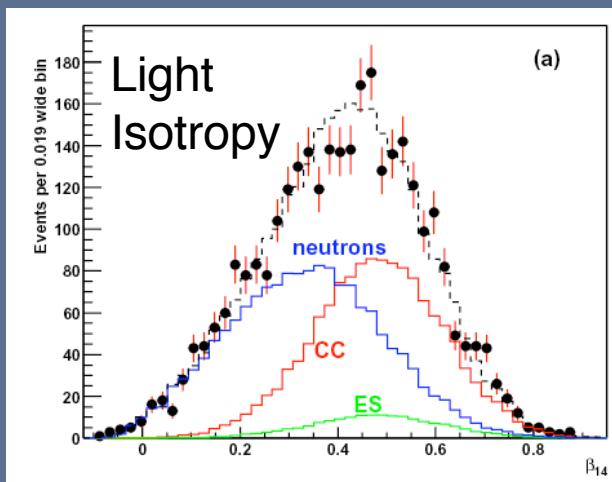
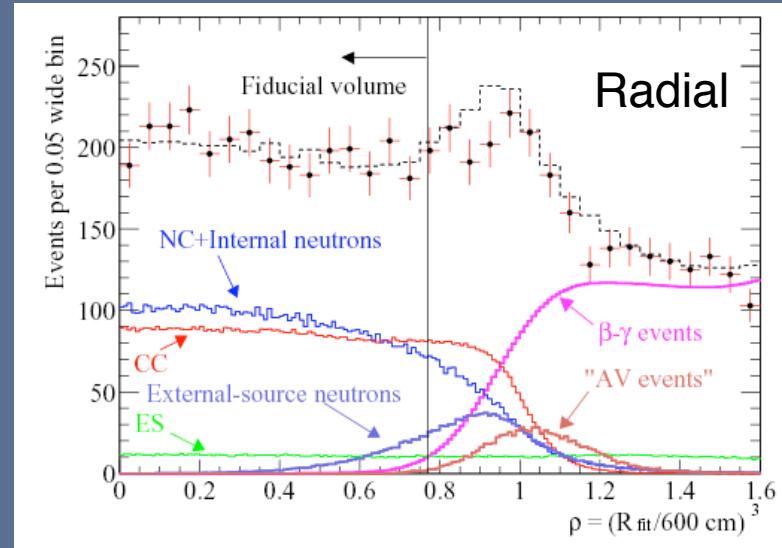
Rule out null hypothesis - no flavor change - at 5.3σ level.

SNO Phase II (salt) Results

nucl-ex/0309004



#EVENTS



SNO Salt Phase - Sept 2003

nucl-ex/0309004



$$\frac{\phi_{\text{CC}}^{\text{SNO}}}{\phi_{\text{NC}}^{\text{SNO}}} = 0.306 \pm 0.026 \text{ (stat)} \pm 0.024 \text{ (syst)}$$

SNO Salt Phase - Sept 2003

nucl-ex/0309004

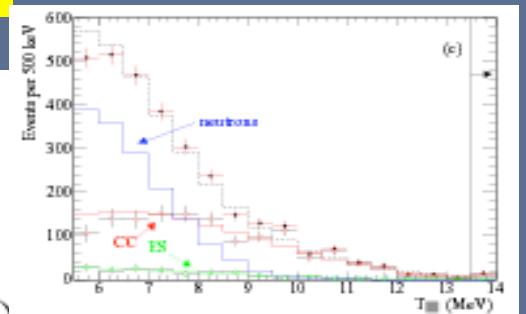


Shape of ^8B spectrum in CC and ES not constrained:

$$\phi_{\text{CC}}^{\text{SNO}} = 1.59^{+0.08}_{-0.07}(\text{stat})^{+0.06}_{-0.08}(\text{syst})$$

$$\phi_{\text{ES}}^{\text{SNO}} = 2.21^{+0.31}_{-0.26}(\text{stat}) \pm 0.10 (\text{syst})$$

$$\phi_{\text{NC}}^{\text{SNO}} = 5.21 \pm 0.27 \text{ (stat)} \pm 0.38 \text{ (syst)}$$



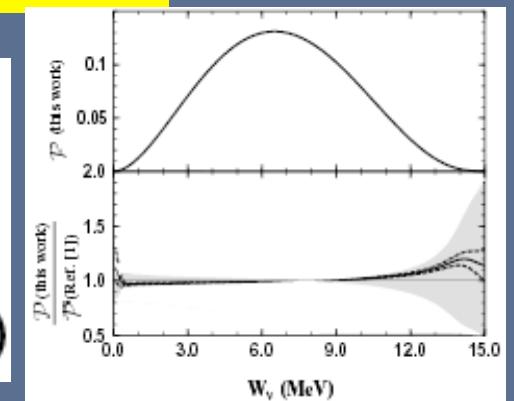
$$\frac{\phi_{\text{CC}}^{\text{SNO}}}{\phi_{\text{NC}}^{\text{SNO}}} = 0.306 \pm 0.026 \text{ (stat)} \pm 0.024 \text{ (syst)}$$

Standard (Ortiz et al.) shape of ^8B spectrum in CC and ES:

$$\phi_{\text{CC}}^{\text{SNO}} = 1.70 \pm 0.07(\text{stat.})^{+0.09}_{-0.10}(\text{syst.})$$

$$\phi_{\text{ES}}^{\text{SNO}} = 2.13^{+0.29}_{-0.28}(\text{stat.})^{+0.15}_{-0.08}(\text{syst.})$$

$$\phi_{\text{NC}}^{\text{SNO}} = 4.90 \pm 0.24 \text{ (stat.)}^{+0.29}_{-0.27}(\text{syst.})$$

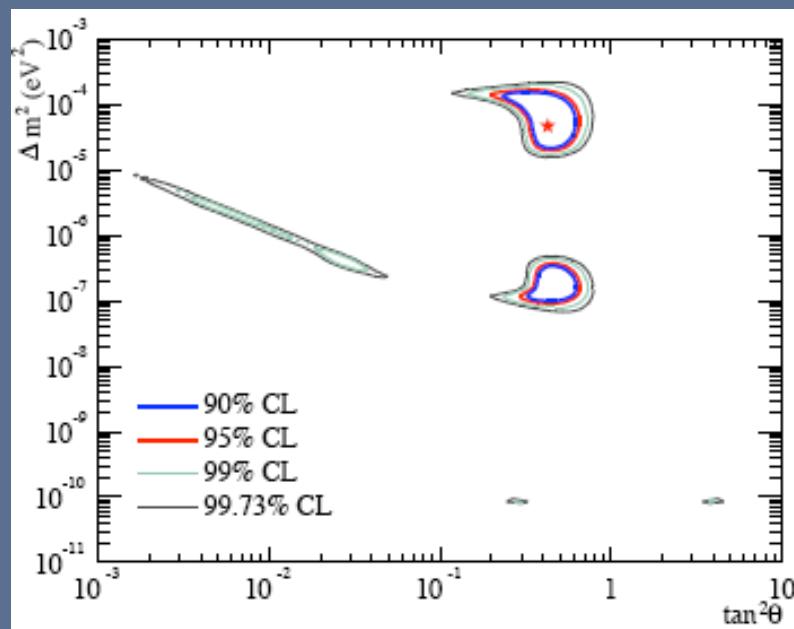


SNO Phase II (salt)

nucl-ex/0309004

$$\phi(^8\text{B})_{\text{meas}} = (0.88 \pm 0.04 \text{ (exp)} \pm 0.23 \text{ (th)}) \phi(^8\text{B})_{\text{SSM}}$$

SNO only 2-ν osc.

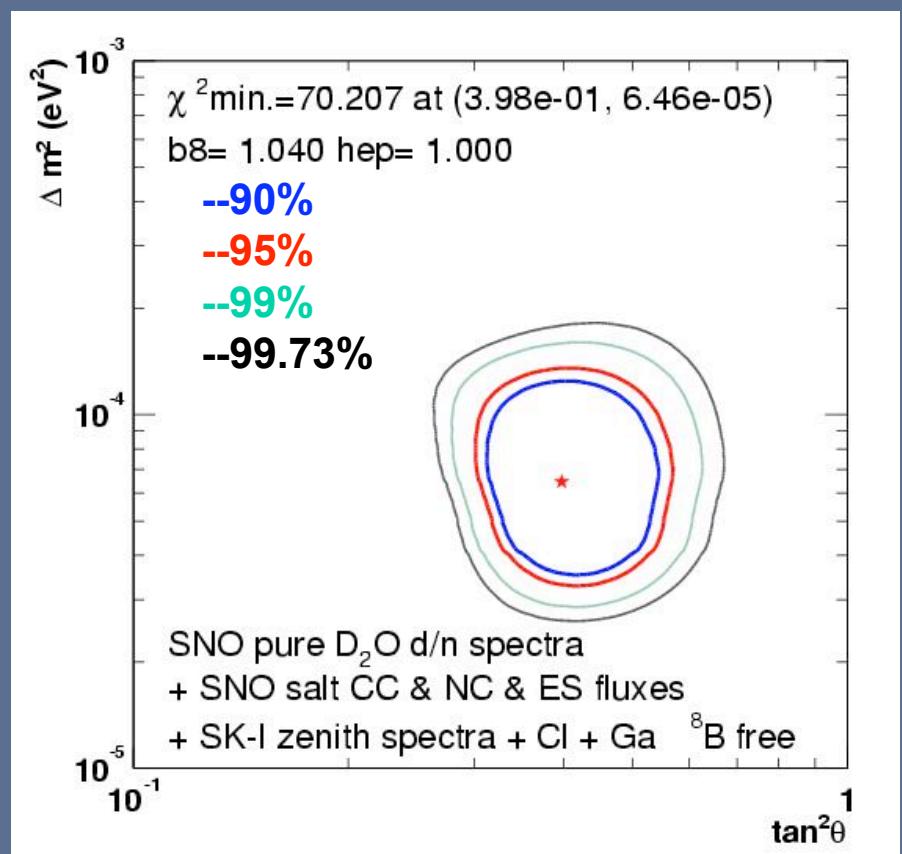


$$\Delta m^2 = 7.1 + 1.0/-0.3 \times 10^{-5} \text{ eV}^2$$

$$\theta_{12} = 32.5 + 1.7/-1.6 \text{ deg}$$

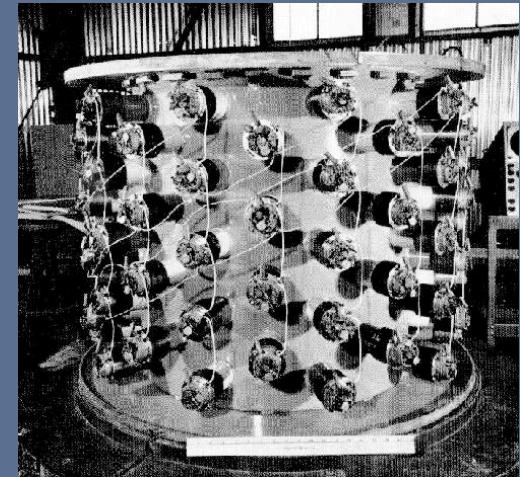
Disfavors maximal mixing at a level equivalent to 5.4 σ.

Global solar ν fit



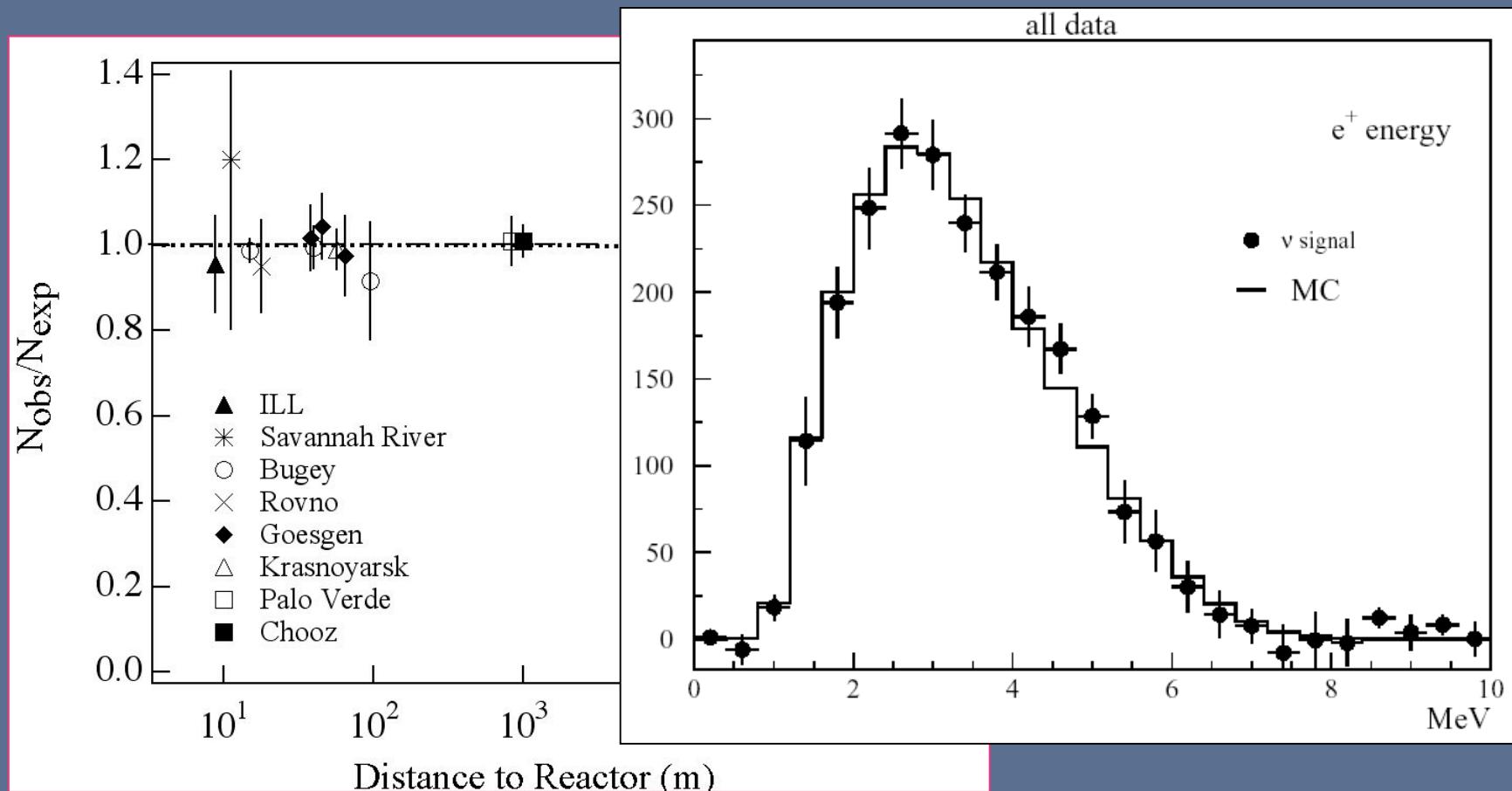
Reactor $\bar{\nu}_e$ oscillation searches

1956 Reines & Cowan $\bar{\nu}_e + p \Rightarrow n + e^+$



Reactor $\bar{\nu}_e$ oscillation searches

1956 Reines & Cowan

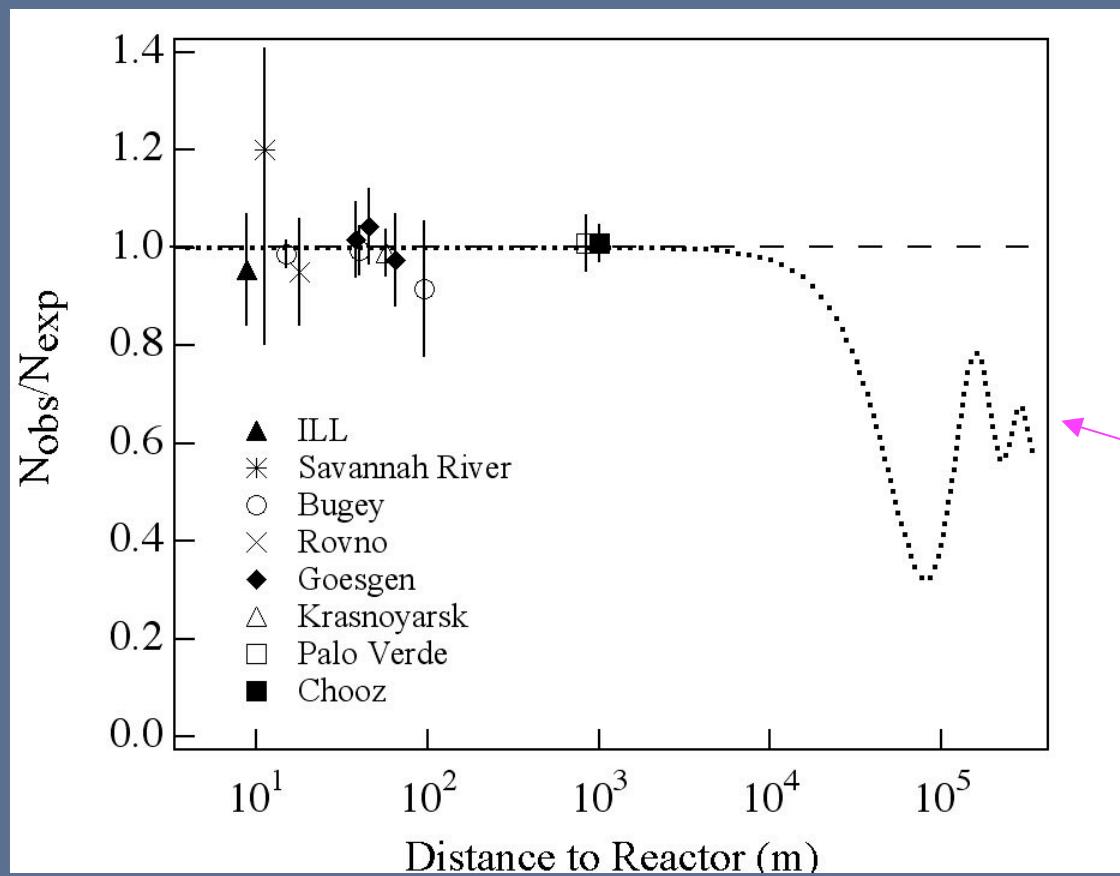


Chooz hep-ex/9907037

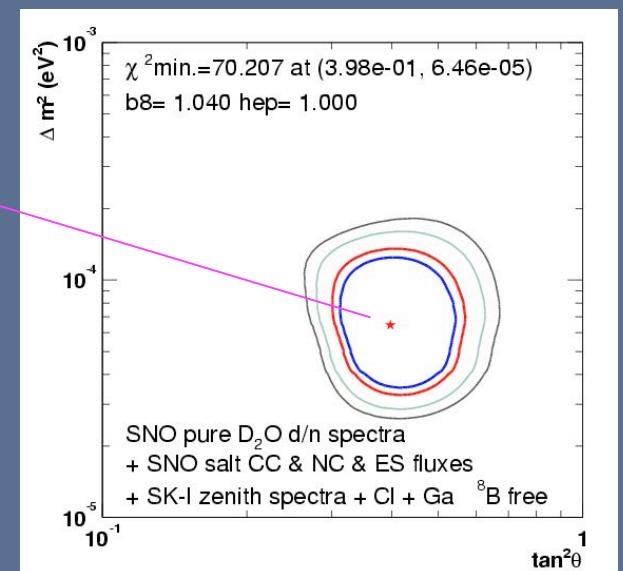
Disappearance experiments

Solar neutrino LMA implication

Reactor experiments optimum at ~ 180 km



Solar LMA best fit prediction





KamLAND Collaboration

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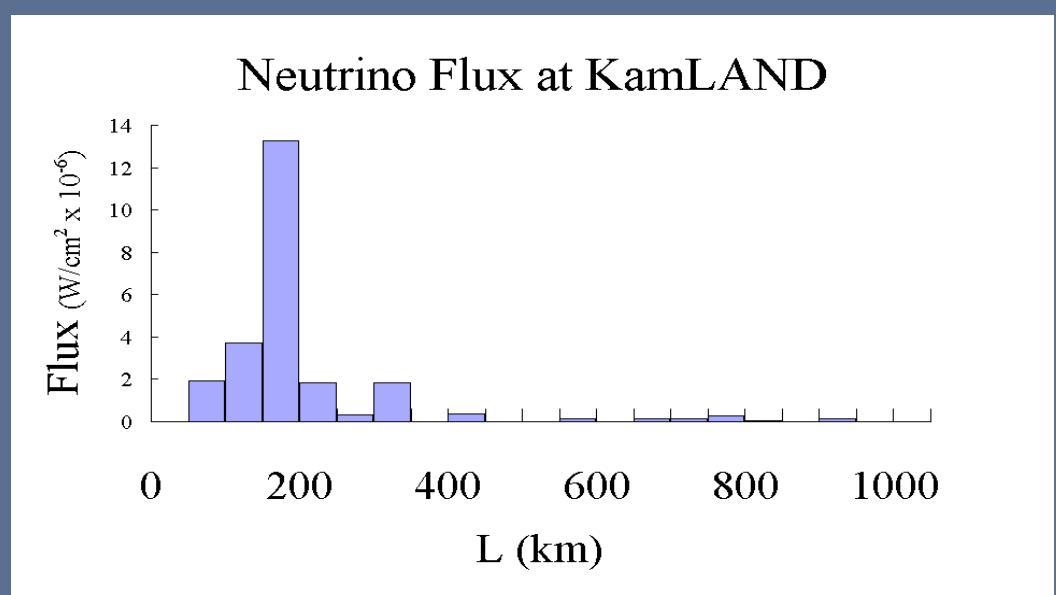
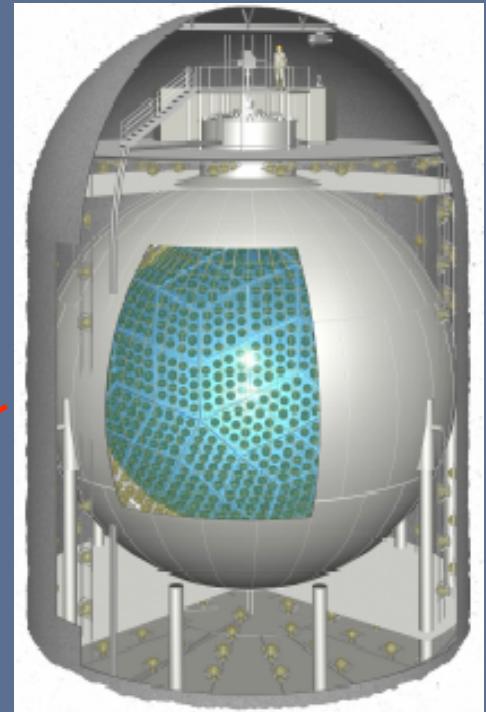
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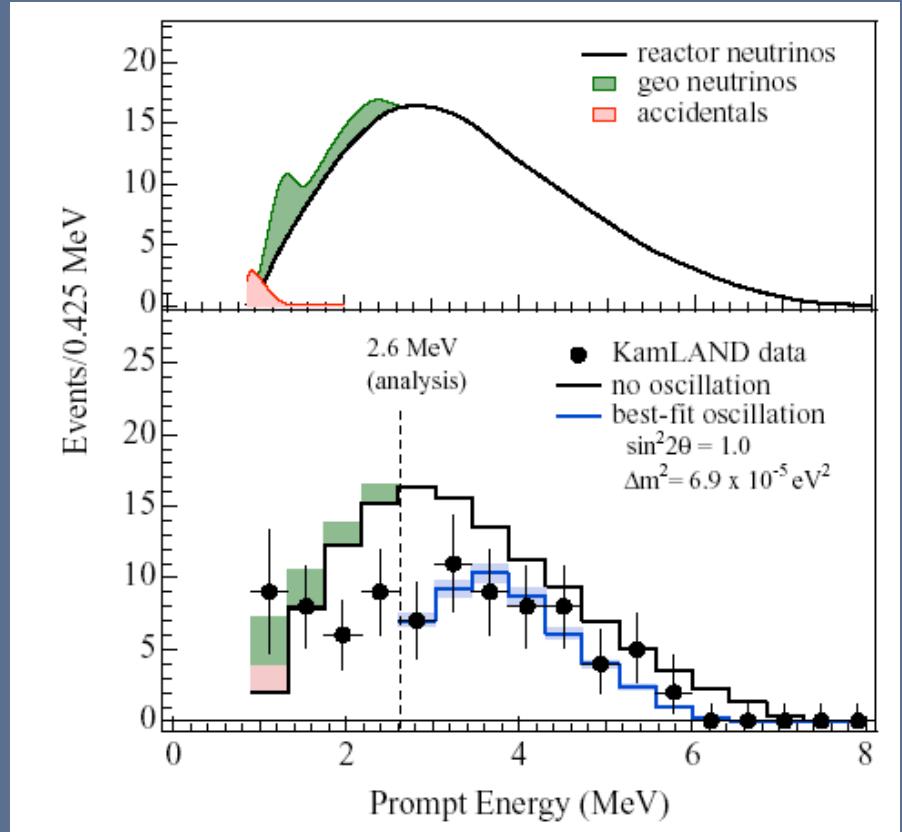
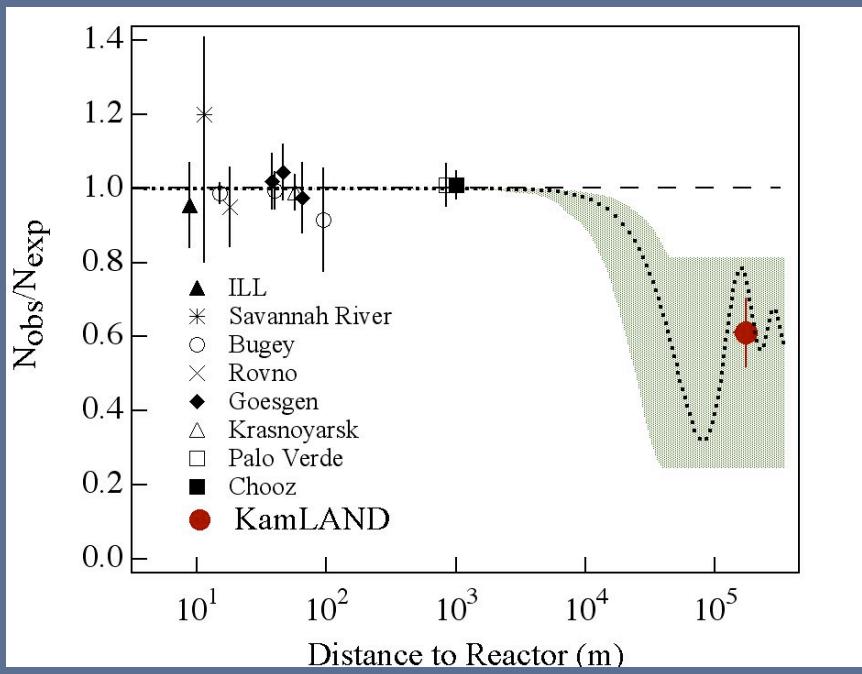
KamLAND - Kamioka Liquid Scintillator Anti-Neutrino Detector





KamLAND first results (hep-ex/0212021)

- Data summary
 - 145.1 live days
 - Observed: 54
 - Expected: 86.8 ± 5.6
 - Background 1 ± 1

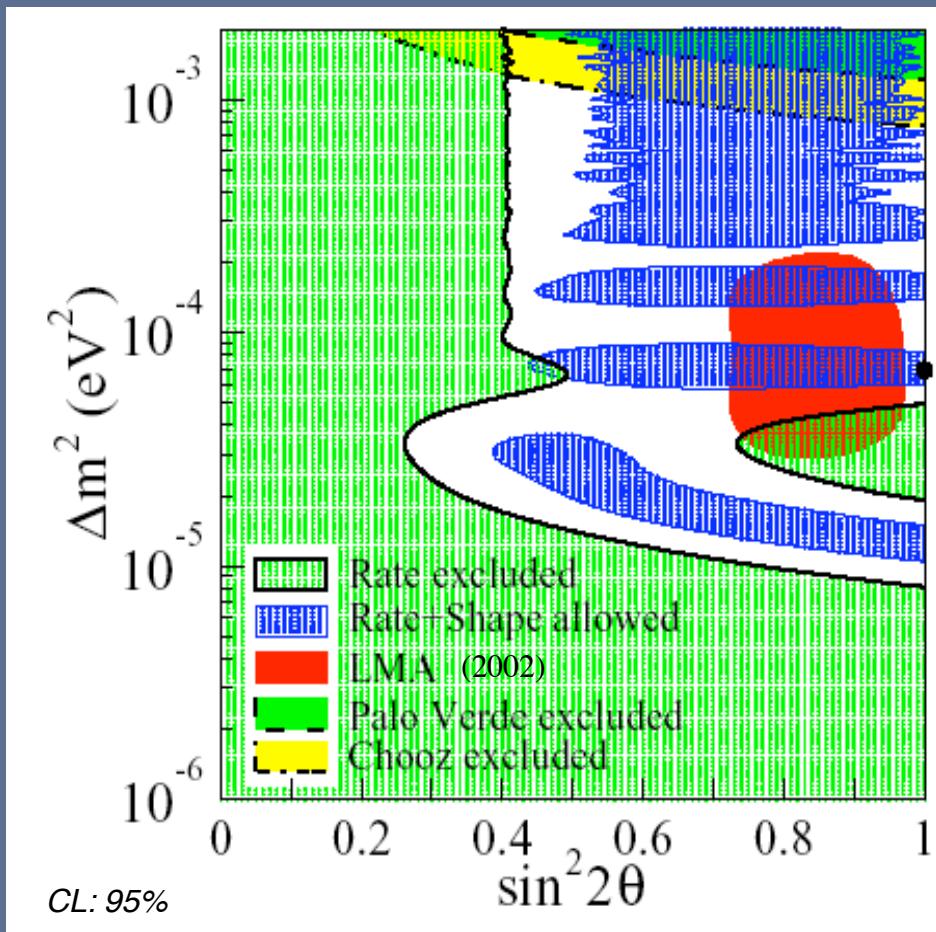


Measured survival probability
differs from 1 by 4.1σ

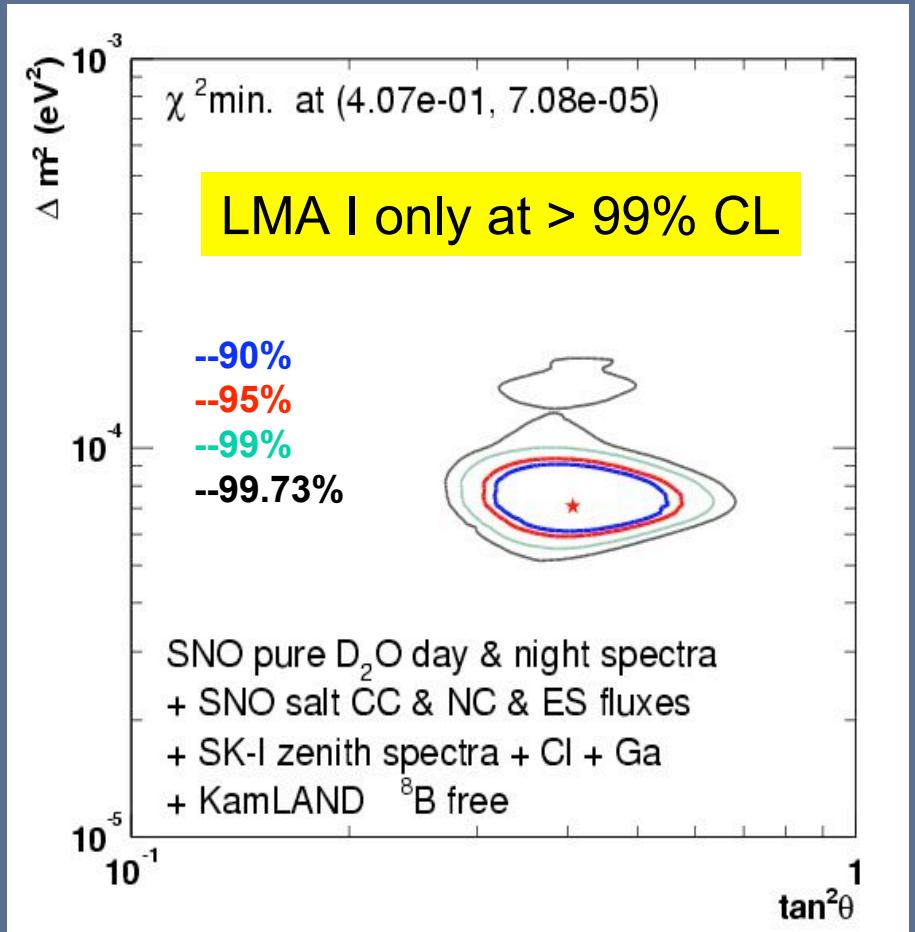
Probability that result is consistent with no
oscillation hypothesis $< 0.05\%$

Evidence of $\bar{\nu}_e$ oscillations

KamLAND with 2002 Solar LMA



Global fit - Solar and KamLAND



hep-ex/0212021

nucl-ex/0309004

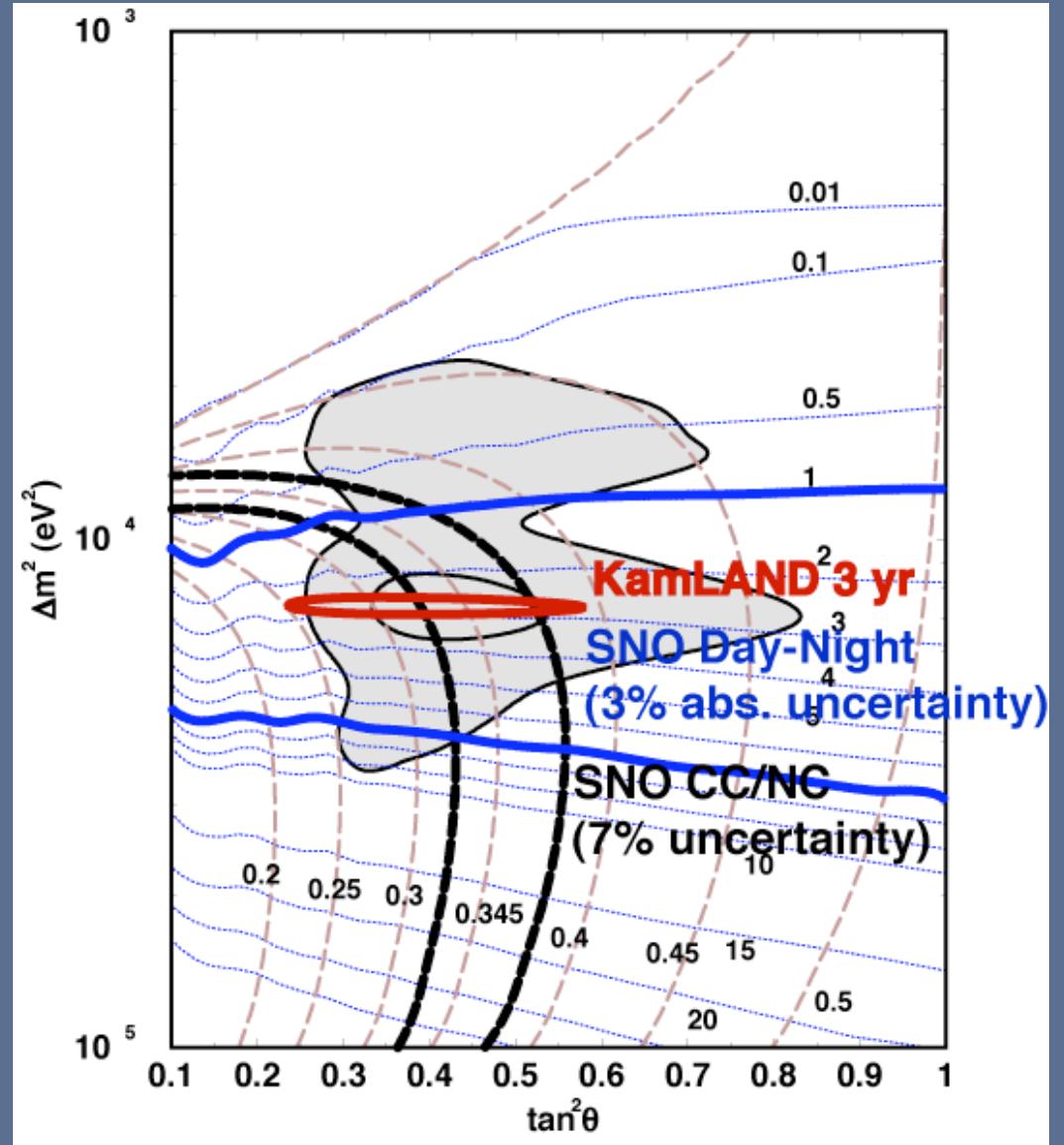
ν physics - issues & questions

The fact that neutrinos that have mass and large mixing angles opens a wealth of interesting theoretical possibilities and experimental opportunities!

- accurate determinations of lepton sector mixing parameters
- absolute scale of neutrino mass
- Majorana/Dirac character of the neutrinos
- lepton number violation
- neutrino magnetic moments (see SuperK hep-ex 0402015)
- CP violation phases?
- existence of, constraints on sterile neutrinos
- inverted or regular hierarchy?
- baryogenesis via leptogenesis
- role of neutrinos in nucleosynthesis, supernova explosions, BBN

Precision ν measurements - future possibilities

- Improved ($\sim 2x$ precision) SNO NC/CC measurement would yield an improved θ_{12} value
- Similar improvement of SNO Day/Night asymmetry would help with Δm_{12}
- KamLAND should improve on Δm_{12}
- Consistency tests
- In 3 n mixing, some constraints on θ_{13}
(Maltoni et al. hep-ph/0309130)



SNO Phase III (NCD Phase)

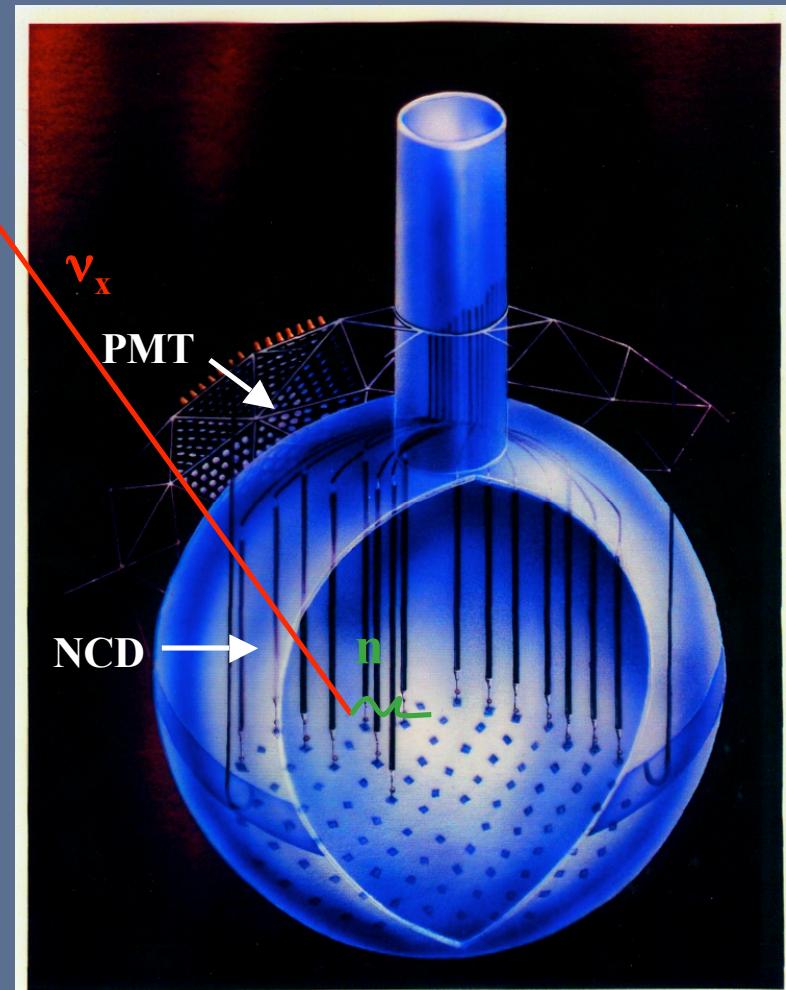
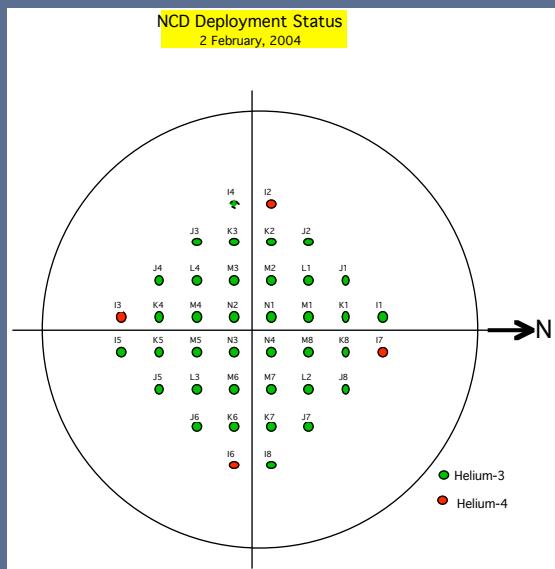
^3He Proportional Counters (“NC Detectors”)

Detection Principle



40 Strings on 1-m grid

398 m total active length



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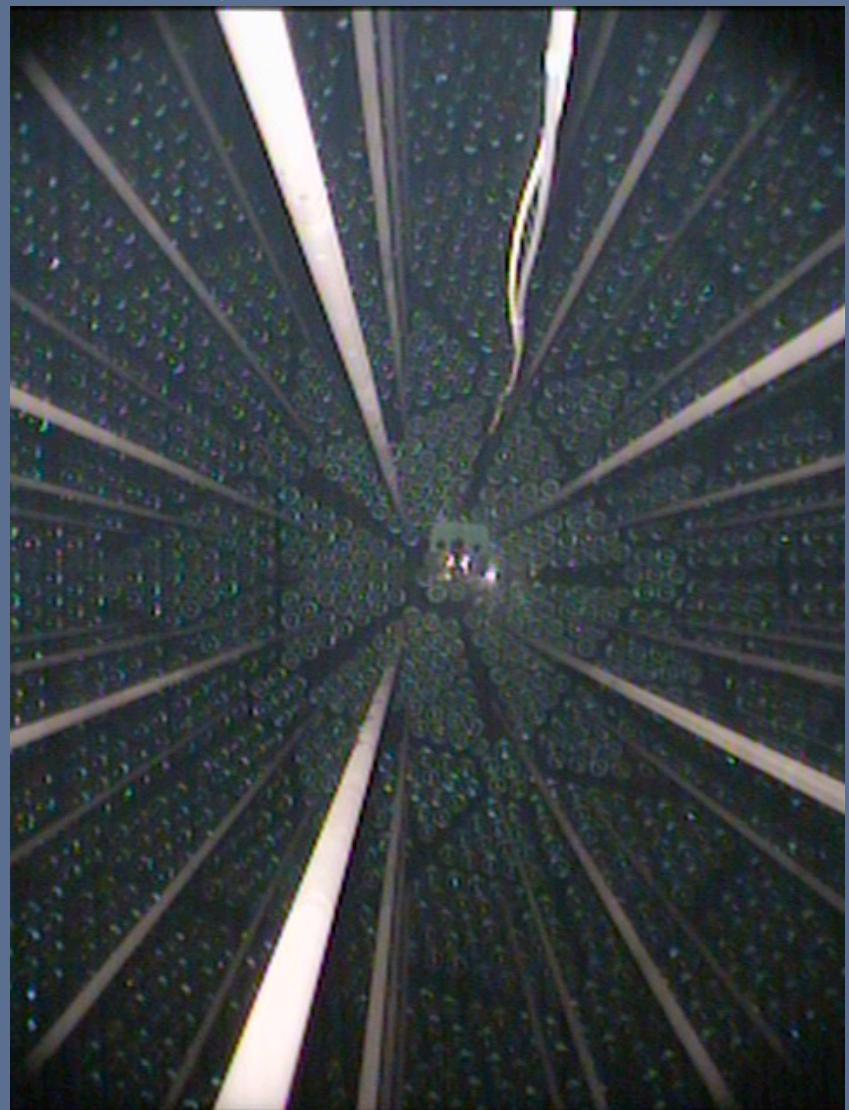
398 m total active length

Physics Motivation

Event-by-event separation. Measure NC and CC in separate data streams.

Different systematic uncertainties than neutron capture on NaCl.

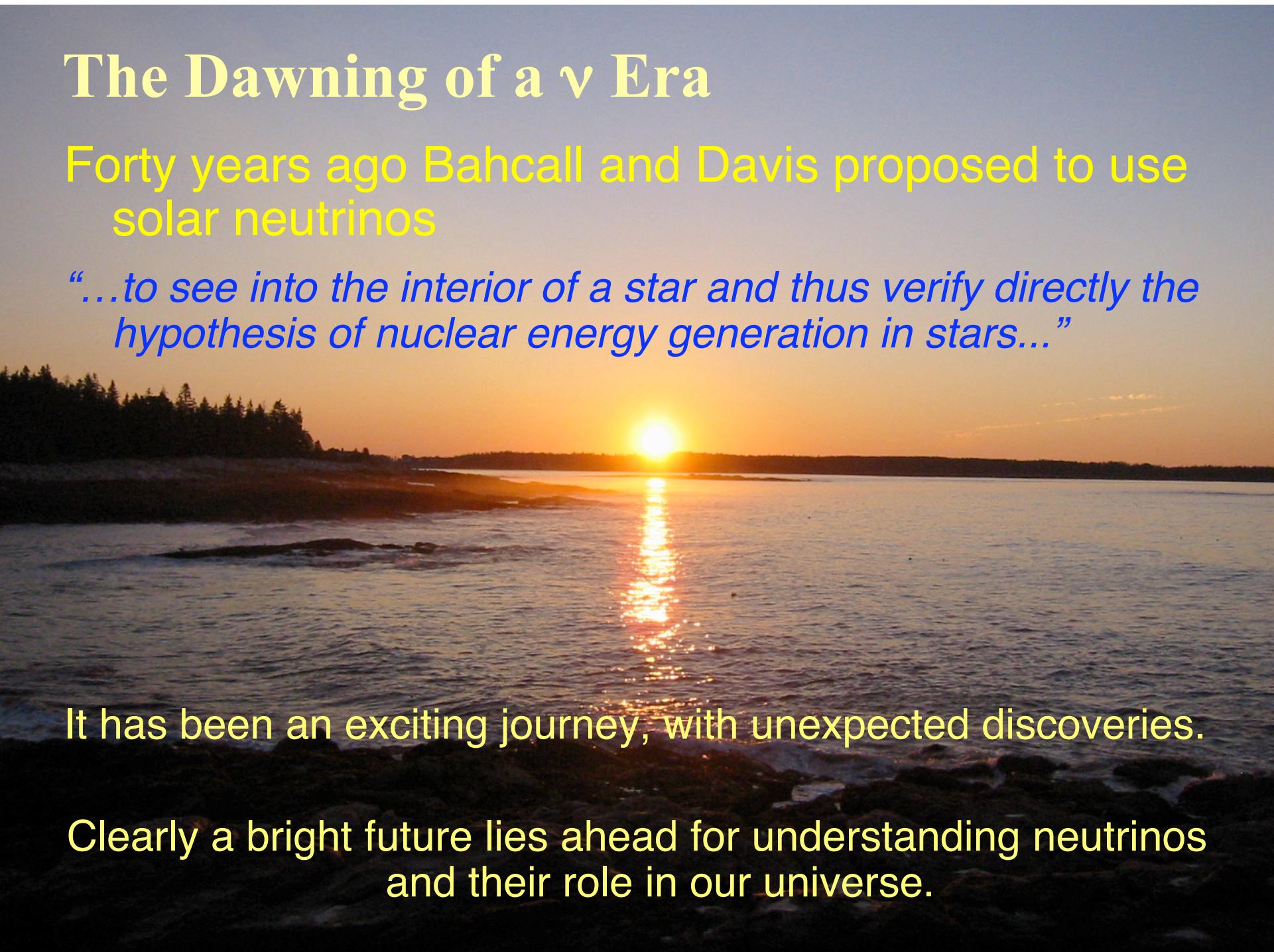
NCD array removes neutrons from CC, calibrates remainder. CC spectral shape.



The Dawning of a ν Era

Forty years ago Bahcall and Davis proposed to use solar neutrinos

“...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars...”



It has been an exciting journey, with unexpected discoveries.

Clearly a bright future lies ahead for understanding neutrinos and their role in our universe.